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ORIGINAL ARTICLE

Microplastic removal using Okra (*Abelmoschus esculentus*) seed from aqueous solutions

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Abstract
The ubiquitous presence of MPs in water bodies presents an escalating concern, as these minuscule plastic particles could ultimately reach humans via the drinking water supply. This study explores the efficacy and underlying mechanisms of removing PE and PVC MPs using *Abelmoschus esculentus* seeds (commonly known as *okra*), a natural and environmentally benign coagulant. Through experiments conducted under varying conditions—such as pH level, coagulant dosage, MP concentration, and EC—using the standard method and a Jar test apparatus, the sedimentation rate was assessed. ZP analysis revealed that charge neutralization and bridging cause pivotal in enhancing the removal efficiency of MPs. FESEM and FTIR analyses corroborated the formation of new bonds during the interaction between the MPs and the *okra* seed-based coagulant. The findings indicate that the optimal parameters for PVC removal were a coagulant dosage of 70 mg/L, a pH of 10, and an MP concentration of 20 mg/L, achieving a removal efficiency of 80.11%. Conversely, for PE, the maximum removal efficiency of 64.76% was realized at a coagulant dosage of 70 mg/L, a pH of 3, and an MP concentration of 20 mg/L. *Abelmoschus esculentus* seeds offer a practical and eco-friendly option, potentially substituting chemical coagulants, to efficiently eliminate MPs from aquatic environments.

Keywords *Okra* seed · Microplastics · Bio-based flocculants · Abelmoschus *esculentus*

Abbreviations

PS	Polystyrene
PVC	Polyvinyl chloride
MPs	Microplastics
EC	Electrical conductivity
ZP	Zeta potential
FESEM	Field emission scanning electron microscopy
FTIR	Fourier transform infrared
NOAA	National oceanic and atmospheric administration
PAHs	Polycyclic aromatic hydrocarbons

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Introduction

Plastic has become an integral part of modern society, with its affordability and durability making it a material of choice across various industries (Frias and Nash 2019). This ubiquity has led to the current era being dubbed the "Age of Plastics" (Zahmatkesh Anbarani et al. 2024). However, the excessive and indiscriminate use of plastic compounds has led to substantial environmental challenges, causing widespread pollution and ecosystem degradation globally. Plastic production and disposal processes emit hazardous chemicals, contaminating soil, water, and air. These contaminants threaten wildlife, destabilize ecosystems, and endanger human health by polluting food chains (Donuma et al. 2024; Yari et al. 2024).

Through mechanical, chemical, and biological decomposition processes, plastics break down into micron-scale and nano-scale particles, collectively known as MPs (Bai et al. 2024; Bajt 2021; Klein et al. 2018). According to NOAA, MPs are defined as plastic particles with a diameter of less than 5 mm (Jahanpeyma and Baranya 2024). These MPs can originate from primary sources, such as industrial production, or secondary sources, where larger plastic items

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degrade over time (Chaudhry and Sachdeva 2021). Once liberated or detached from their initial plastic products, MPs can navigate through watercourses and disperse across a wide array of environments. These include oceans, wastewater treatment facilities, coastal regions, marine sediments, surface waters, freshwater ecosystems, and even glacial landscapes in the Arctic and Antarctic (Barari and Bonyadi 2023; Zahmatkesh Anbarani et al. 2023b; Zhou et al. 2024).

Their small size and large surface area (Enfrin et al. 2020; Yang et al. 2019) allow them to adsorb a range of hazardous compounds, including PAHs, cyanide (Bonyadi et al. 2012), pesticides (Pirsaheb et al. 2013), antibiotics (Li et al. 2018; Lotfi Golsefidi et al. 2023), polychlorinated biphenyls (Pathak et al. 2020), and heavy metals (Bai et al. 2022; Zafarzadeh et al. 2021). This capability underscores the potential risk MPs pose to both terrestrial and aquatic ecosystems, as well as human health, due to their capacity to accumulate and concentrate these harmful substances. The ingestion or inhalation of MPs by marine organisms (Botterell et al. 2019; Egbeocha et al. 2018) and even humans has raised significant ecological and health concerns. MPs have the unique capability to permeate cell membranes across various organs, leading to disruptions in the normal functioning of critical biological systems. These pollutants affect the digestive, respiratory, nervous, and endocrine systems, potentially leading to systemic disruptions (Esmaeili Nasrabadi et al. 2023). In the digestive system, MPs can cause physical damage and alter the intestinal microbiome, impacting digestion and potentially leading to secondary poisoning from adsorbed toxins. Respiratory issues arise from inhalation of MPs, inducing inflammation and oxidative stress in the lungs, which can progress to chronic obstructive pulmonary disease COPD and other respiratory conditions (Barari et al. 2024). The nervous system may also be affected indirectly through systemic inflammation and oxidative stress, though direct links to neurological effects are still emerging. Endocrine disruption occurs due to MPs' interference with hormone production and metabolism, leading to a range of health issues, including thyroid dysfunction and reproductive disorders (Bajt 2021; Kim et al. 2021; Shi et al. 2023).

Research indicates the presence of MPs in both surface water and sediment samples from various rivers across Iran, notably in the Zayandeh-rud River, where 588 items per kilogram of dry weight were detected (Behmanesh et al. 2023; Rami et al. 2023). Moreover, MPs have been identified in the effluent of wastewater treatment plants, specifically in District 22 of Tehran, averaging 2.15 MPs particles per (Feizi et al. 2022). Among the various types of MPs found in water bodies, PS and PVC are of particular interest, as their densities are similar to that of natural water (Almujally et al. 2024; Fernández-González et al. 2022; Lee et al. 2021). Freshwater ecosystems have been increasingly recognized as an important source of MPs in the oceans, warranting greater attention (Lee et al. 2021).

Removal of pollutants from aquatic environments employs a variety of methods, including membrane reactors (Mishra et al. 2022), rapid sand filtration (Bayo et al. 2020), photocatalysis, absorption (Padervand et al. 2020), and coagulation processes such as flocculation (Gao and Liu 2022; Ma et al. 2019b). Biological treatments involving organisms like algae (Esmaili et al. 2023; Nasoudari et al. 2023) and yeasts (Anbarani et al. 2023; Mazloomi et al. 2021) are also utilized. A notable observation from reviews indicates the successful removal of PS particles from water using polyaluminum chloride as a coagulant (Li et al. 2021; Liu et al. 2022).

The imperative to maintain environmental equilibrium, protect public health, and preserve the integrity of the food chain has propelled the investigation and adoption of natural coagulants as a compelling alternative to chemical options (Nasrabadi et al. 2023b). The use of natural, sustainable coagulants, such as starch, *okra* (Badawi et al. 2023) cellulose (Yu et al. 2016; Zhu et al. 2015), pectin (Ibarra-Rodríguez et al. 2017), chitosan (Badawi et al. 2023), lignin (Couch et al. 2016), plant gum (Shahadat et al. 2017) and microbial flocculants (Zahmatkesh Anbarani et al. 2023a), has shown promising results in addressing this issue. In the present study, the highest removal efficiency of PE MPs was achieved at 84% using *C. vulgaris* (Eydi and Bonyadi 2023). The *okra* (*Abelmoschus esculentus*) plant from the Malvaceae family is known as gumbo or lady's fingers (Sayyad et al. 2024). The plant has a straight stem, covered with webs and a height of 0.5 m, sometimes 2 m. *Okra* seed is rich in carbohydrates, tanen and contains a large amount of water-soluble polysaccharides that can create very high viscosity in low concentrations (Yu et al. 2024). *Okra* polysaccharide is an acidic polysaccharide and consists of galactose, rhamnose and galactonic acid. The polysaccharide content in *okra* seed extract is responsible for its viscous texture and exhibits promising coagulation properties. This suggests the presence of active sites capable of effectively adsorbing colloids during the coagulation-flocculation process (Agarwal et al. 2001). These features render it a highly appealing choice for the removal of diverse pollutants, including MPs, from aqueous solutions (Chung et al. 2018; Lanan et al. 2021). In a study, *okra* polysaccharide removed 87% of MPs from water samples (Bhuju 2020). *Okra* seed is an effective coagulant to remove turbidity (Fahmi et al. 2014). The ability of *okra* polysaccharides to form strong bonds with particles makes them a promising natural and sustainable solution for various particle removal applications, including wastewater treatment (Oladoja 2015).

Considering the numerous benefits of *okra*, it becomes crucial to utilize *okra* seeds for the removal of MPs such as PS and PVC. The main goal is divided into two objectives:

(1) to clarify the underlying coagulation mechanisms that facilitate the efficient removal of PVC and PS MPs, and (2) to thoroughly investigate the impact of various operational factors, such as pH, coagulant dosage, MP concentration, and EC, on the overall removal efficiency of these contaminants.

Materials and methods

Chemicals and reagents

Chemicals with a purity level of 95%, including sodium hydroxide, hydrochloric acid, sodium chloride, and sodium sulfate, were procured from Merck, Germany. Additionally, Whatman filter paper with a pore size of 0.45 microns was sourced from Merck, Germany.

Preparation of microplastics

The PS MP used in this experiment was purchased in the form of transparent granules from Mashhad Tos Polymer Company. The PS granules were ground and sieved to obtain particles smaller than 100 µm. PVC MPs with a size of less than 85 µm were obtained from Mashhad Tos Polymer Company. To minimize potential interference and ensure proper contact between *okra* particles and MPs, the raw *okra* seeds were washed with distilled water. Subsequently, the materials were dried for 12 h at 60 °C. The resulting MPs were then stored in a sealed container, protected from moisture and light, in a dark environment.

Preparation of *okra* seed

Okra was bought from a market in Mashhad. Iran. The seeds were manually removed from the pods. The seeds underwent a thorough cleansing process using laboratory-distilled water to eliminate contaminants such as stones, plant debris, and dust, which may affect their integrity and quality. Following the washing step, the cleaned seeds were subsequently dried in an oven at 60 °C for 6 h (Fig. 1). After drying, the seeds were ground into a powder and were passed through a 400 µm sieve for granulation.

Coagulation experiments

Various parameters were considered to evaluate the removal efficiency of PVC and PS MPs by *okra* seeds. These parameters included the initial concentration of MPs (20, 50, 100 mg/L), the dose of *okra* seed (10, 40, 70 mg/L), the pH levels (3, 7, 10), and EC (0.05, 2500–5000, > 5000 mS/cm). The removal process was conducted using the jar test method (Richmond, VA 23228) at room temperature (25 ± 2 °C). The stirring speed was set to 150 rpm for 3 min, followed by 20 rpm for 20 min. Afterward, the suspension was transferred to a decanter funnel, and the formed flocs were allowed to settle undisturbed for a duration of 1 h. Following the settling period, the liquid above the settled flocs was filtered, and the filtrate was subsequently dried at 60 °C for a period of 24 h. The final weight of the filter paper was subtracted from the initial weight to determine the weight of the remaining MPs. The removal efficiency of MPs was calculated using the following formula:

$$R(\%) = \frac{M_1 - M_2}{W} \times 100\% \quad (1)$$

where M_1 represents the initial weight of MP before the removal process, M_2 represents the weight of MP on a Whatman filter after the removal process, and W represents the mass of MP (Eydi Gabrabad et al. 2024).

Fig. 1 **a** raw *okra* cut into pieces, **b** dried *okra* seeds

Characteristics and measurements

The MPs and flocs that precipitated in the lower layer were collected for characterization. FTIR (FTIR/NIR FRONTIER model) was used to identify the functional groups present on the surfaces of *okra* seeds, MPs, and the bio-based flocculants. FESEM (Carl Zeiss model, Germany) was employed to investigate the surface morphology of the samples under study. ZP (Oxford model connected to a JEOL-JSM-5600 SEM) was used to measure the surface charge and the amount of repulsion or attraction of the samples under study.

Statistical data analysis

The number of tests was determined employing a single-factor experimental design. Within each trial, one variable was altered while the remaining variables were held constant at their optimal levels. Subsequent data analysis was conducted utilizing SPSS version 22.0. ANOVA was executed to evaluate sample differences, applying a minimal significant difference criterion (P-Value < 0.05).s

Result and discussion

Effect of double-layer compression

To elucidate the coagulation mechanism, it is imperative to investigate the process of charge neutralization during coagulation. ZP assesses the electrostatic dispersion process and serves as an indicator of particle stability. It is influenced by several parameters, such as pH, solution conductivity, and particle concentration. Table 1 displays the ZP values of the MPs utilized in the coagulation experiments, as well as the ZP of the supernatant following the reaction. ZP values for PVC and PS were obtained as − 79.6 and − 78 mV, respectively. After coagulation, the ZP of PVC at alkaline pH was − 52.4 mV, whereas under acidic conditions, the ZP of PS was approximately − 54.5 mV. The addition of *okra* seeds into the suspension diminishes the repulsive force acting between the particles, facilitating the formation of bio-based flocculants. As a result, these flocs gradually settle due to their heightened density, indicating the potential of *okra* seeds to impact the settling and subsequent removal of PVC and PS particles from the environmen (Zhang et al. 2021). The charge of the colloidal particles and the absolute value of the ZP of the MPs both decreased as a result of this process, indicating charge neutralization and the compression of the electrical double layer of the MPs (Zhang et al. 2021). The final ZP in the PVC-*okra* seed system was closer to zero potential than that in the PS-*okra* seed system, illustrating that the charge neutralization in the PVC-*okra* seed system was more effective.

Table 1 Zeta potential of *okra* seed, PVC and PS MPs before and after coagulation

Sample name	Zeta potential	Electrophoretic mobility
PVC	− 79.6 mV	− 0.000619 cm^2/Vs
PS	− 78 mV	− 0.000606 cm^2/Vs
okra seed	− 49 mV	− 0.000380 cm^2/Vs
PVC + *okra* seed	− 52.4 mV	− 0.000406 cm^2/Vs
PS + *okra* seed	− 54.5 mV	− 0.000423 cm^2/Vs

The presence of electrostatic repulsion between the MPs and the negatively charged coagulant indicates that charge neutralization is not the sole dominant mechanism at play. Most polyelectrolytes, like *okra* seeds, have hydrogen atoms that are covalently attached to a more electronegative atom or group such as carboxylic, amide, amine, and hydroxyl and can form hydrogen bonds with other electronegative atoms that have alone pair of electrons (Tosif et al. 2021). The availability of a large number of hydroxyl groups (polar agent) in the galactone chain increases the absorption of these polymers on the surface of the pollutant particles and also increases the bridging action between the pollutant (Koul et al. 2022). In addition, a mixture of polysaccharides such as galactomannan and galactan isolated from tannin seeds, cactus, Nirmali and Strychnos potatorum have the ability to reduce turbidity (Dwarapureddi and Saritha 2016; La Mer 1966). Furthermore, the decrease in electrophoretic mobility after the reaction in Table 1, can be related to the efficiency of the coagulation processes for MP removal (Martic et al. 2022). An efficient coagulation process can effectively agglomerate MPs and lead to a decrease in their electrophoretic mobility (Azizi et al. 2023).

Effect of adsorption

In addition to charge neutralization and bridging, adsorption plays a crucial role in the coagulation process. As shown in Fig. 2, the joint morphology of MPs and loaded flocs in the PVC + *okra* seed system was analyzed by FESEM. Based on Fig. 2a, it can be observed that PVC exhibits a non-uniform surface with spherical chains, along with significant valleys and grooves. These surface characteristics of PVC are advantageous (Suganya et al. 2016), as they provide a substantial surface area and active sites for adsorption. This enables PVC to effectively carry other particles and pollutants (Ren et al. 2021). Yu et al. (2020) demonstrated that PVC may possess a higher number of adsorption sites

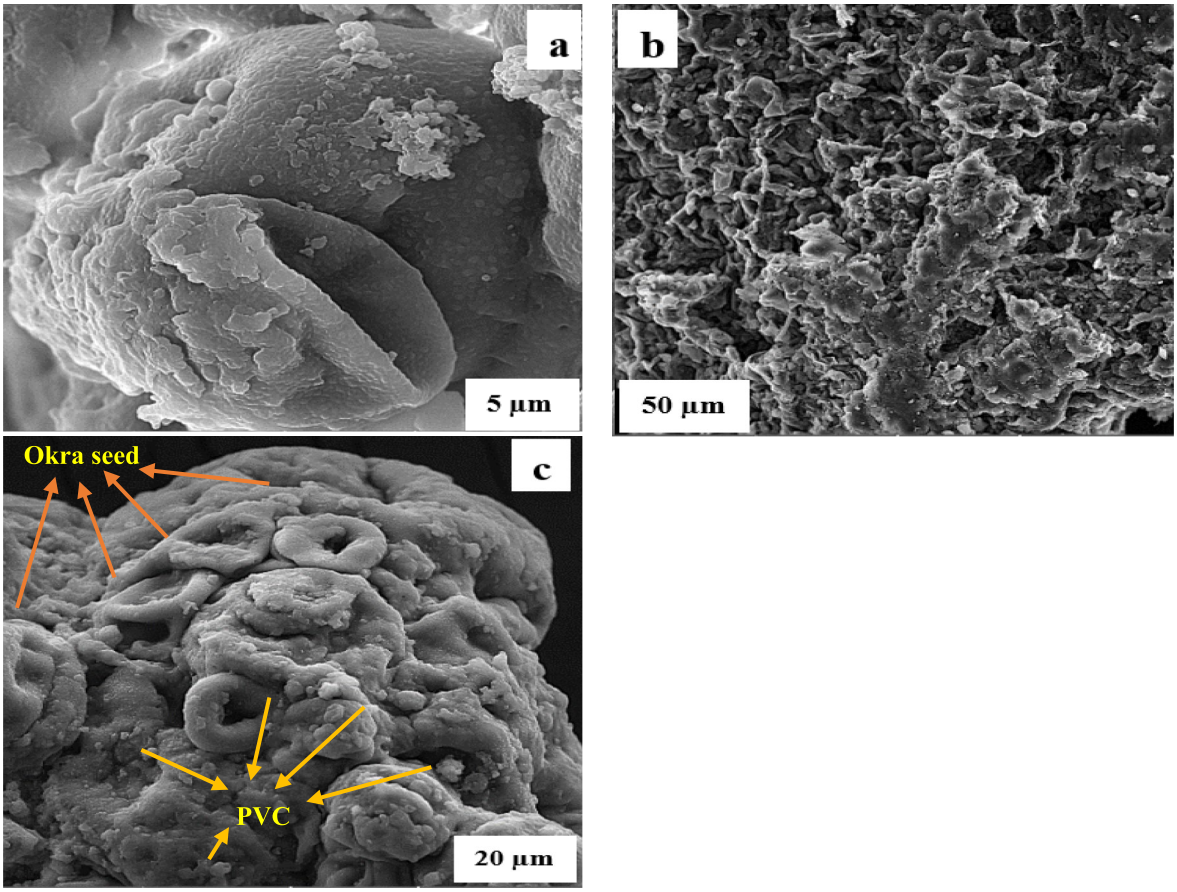

Fig. 2 FESEM of **a** PVC, **b** *okra* seed and **c** bio-based flocculants

compared to other MPs due to its rough surface and internal wrinkles (Yu et al. 2020).

As shown in Fig. 2b, the *okra* structure looks spongy and compact, and this porosity is caused by transverse connections. This porous structure prepares minimal matrix space, enabling the ingredients to be incorporated more efficiently into the tablet (Zaharuddin et al. 2014). As depicted in Fig. 2c, the flocs formed after the elimination process consist of a combination of *okra* seeds and PVC particles. The entanglement and accumulation of MPs and *okra* seeds are evident, signifying the adsorption and bridging of MPs by *okra* seed cells (Khan et al. 2023). The interaction between the pores and gaps present in *okra* seed particles and the uneven surface of MPs results in the formation of larger flocs. Consequently, these flocs settle at an accelerated rate due to their increased size and weight (Fahmi et al. 2014). In conclusion, the adsorption of PVC onto the *okra* particles as well as the bridging effect of the *okra* seed contributes to the effective coagulation and sedimentation of the MPs.

From Fig. 3d, it can be observed that PS particles have irregular cracks on their surfaces (Kurniawan et al. 2023; Zhou et al. 2021). Figure 3f presents the FESEM image depicting the coagulation of PS particles post-treatment with *okra* seeds. The image clearly demonstrates the entanglement and accumulation of the MP particles and okra. This visual evidence indicates the effective adsorption and bridging of the PS MPs by the *okra* seed (Zhou et al. 2021). The interaction between the porous and spongy structure of the *okra* seed and the uneven surface of the PS MPs appears to be a key factor driving the coagulation process. Also Kurniawan et al. (2023) stated that the irregular cracks of PS particles lead to an increase in the contact surface with polymer particles. (Kurniawan et al. 2023; Wang et al. 2024).

FTIR analysis was used to investigate the chemical composition and interactions between the PVC and the *okra* seeds. According to Fig. 4, the FTIR spectrum of the *okra* seeds reveals the presence of several functional groups that contribute to the coagulation mechanism. The broad peak observed at 3423.140 cm^{-1} indicates the presence of aromatic sugar groups with O–H as the main functional group (Zaharuddin et al. 2014). These hydrophilic O–H groups act as active sites, facilitating the binding of colloidal particles and metal ions (Di Bernardo and Dantas 1993). The peak at 2927.64 cm^{-1} corresponds to the C–H stretching vibrations

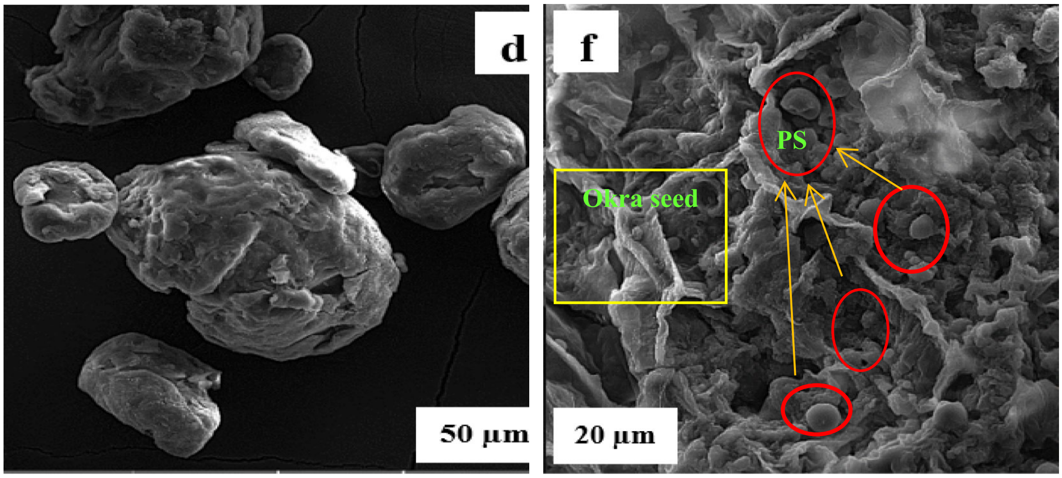

Fig. 3 FESEM of **a** Ps and **b** Bio-based flocculants

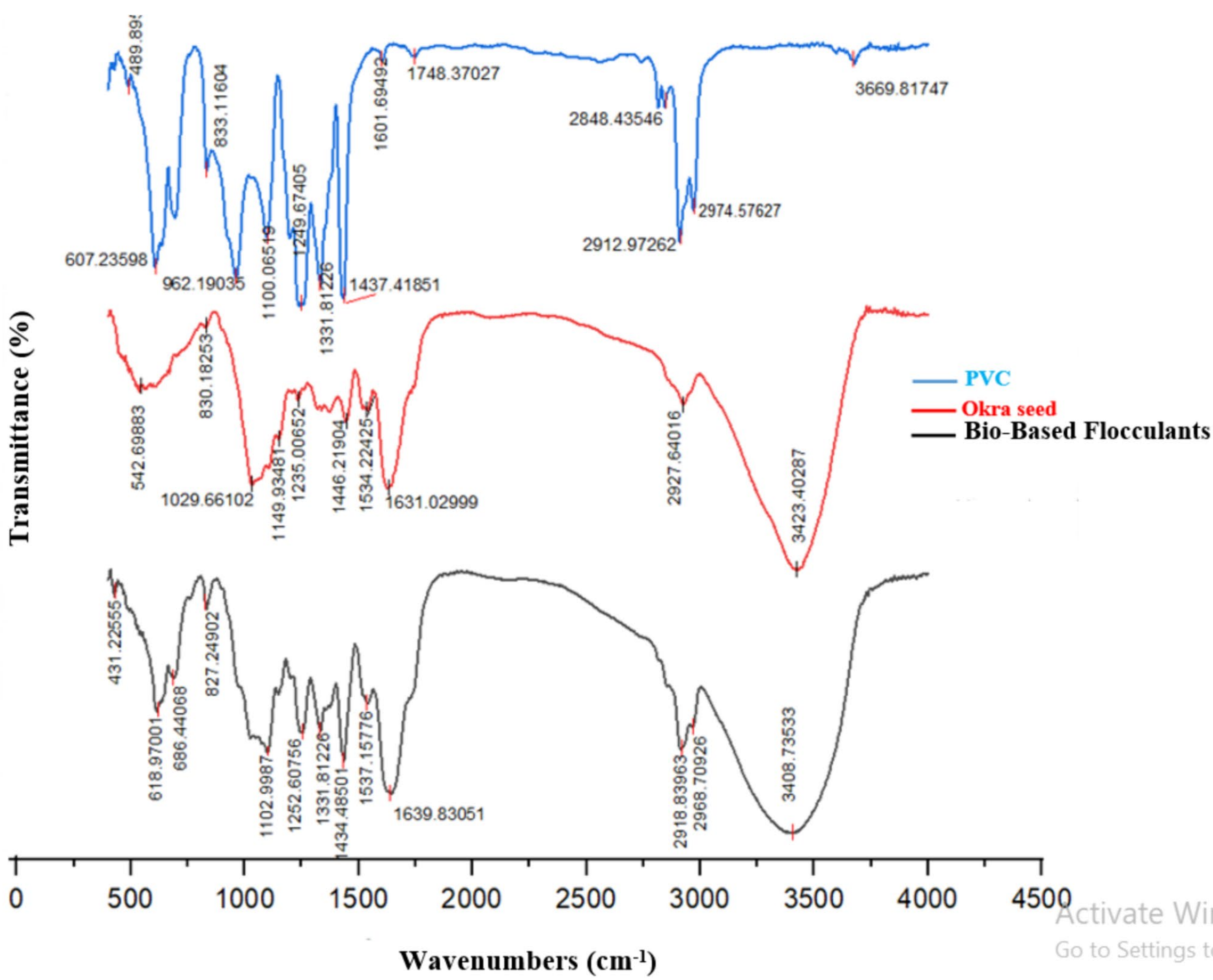

Fig. 4 FTIR spectrum of PVC, *okra* seed and bio-based flocculants

of the methyl and methylene groups present in the cellulose and hemicellulose components, such as galactose and rhamnose (Zaharuddin et al. 2014). Additionally, the peak at 1631.102 cm^{-1} is attributed to the C=O stretching vibrations of carboxylic acids, esters, and amides, indicating the possible attachment of N, N-methylene bisacrylamide to the *okra* structure (Rahman et al. 2018). The presence of these functional groups suggests that the *okra* seeds possesses the necessary characteristics to effectively interact with and coagulate the PVC MPs (Wang et al. 2023).

In the infrared spectrum related to PVC in Fig. 4, a prominent peak is observed at 3669.81 cm^{-1}, which corresponds to the stretching vibrations of the O–H hydrogen bond (Lu et al. 2022). Additionally, peaks at 2974.57 and 2912.97 cm^{-1} are attributed to the C–H stretching vibrations, while the peak at 1331.18 cm^{-1} is associated with the C–Cl stretching vibrations (Wu et al. 2014). Figure 4 indicates that the peak corresponding to the O–H groups decreased to 3408.73 cm^{1}. Furthermore, the CH_2 asymmetric stretch exhibits a significant decrease, measuring 2918.183 cm^{-1}, compared to the peak observed prior to the removal process (He et al. 2023). The peak at 1639.183 cm^{-1} is related to amine groups in *okra*, which reduce the repulsive force between PVC particles. The peak corresponding to the O–H group decreased from 1446.121 to 1434.48 cm^{-1}. This reduction may be attributed to the formation of flocs caused by the adsorption of PVC on *okra*. When *okra* is adsorbed on PVC, the molecules interact with chlorine atoms in PVC, leading to a peak shift from 833.11 to 827.24 cm^{-1}. The appearance of C–H and O–H groups after the adsorption process shows that *okra* molecules are connected to PVC through hydrogen bonding (Atugoda et al. 2020). Hydrophilic groups, the cellulose and hemicellulose components, and the carbonyl amide groups in the *okra* seed play a crucial role in the coagulation of the PVC MPs (Kim et al. 2020). Amide, amine, carbonyl, and methylene groups play a crucial role in charge neutralization and point flocculation mechanisms during coagulation-flocculation processes (Chum 2020; Magalhães et al. 2021).

The FTIR spectrum of the PS in Fig. 5 shows prominent peaks around 3438.10 and 2915.9 cm^{-1} are attributed to –OH and C–H stretching vibration, respectively. The peak in the region of 1745.143 cm^{-1} is related to the C=O group (da Silva et al. 2008). The peak at 1602.169 cm^{-1} was attributed to the C=C stretching band. The presence of absorption peaks at 906.45, 753.91, and 533.89 cm^{-1} is related to C–H bending band, C–H stretching band, and C–H stretching band, respectively. The peaks at around 841.91 and 753.91 cm^{-1} corresponded to the substitution of the

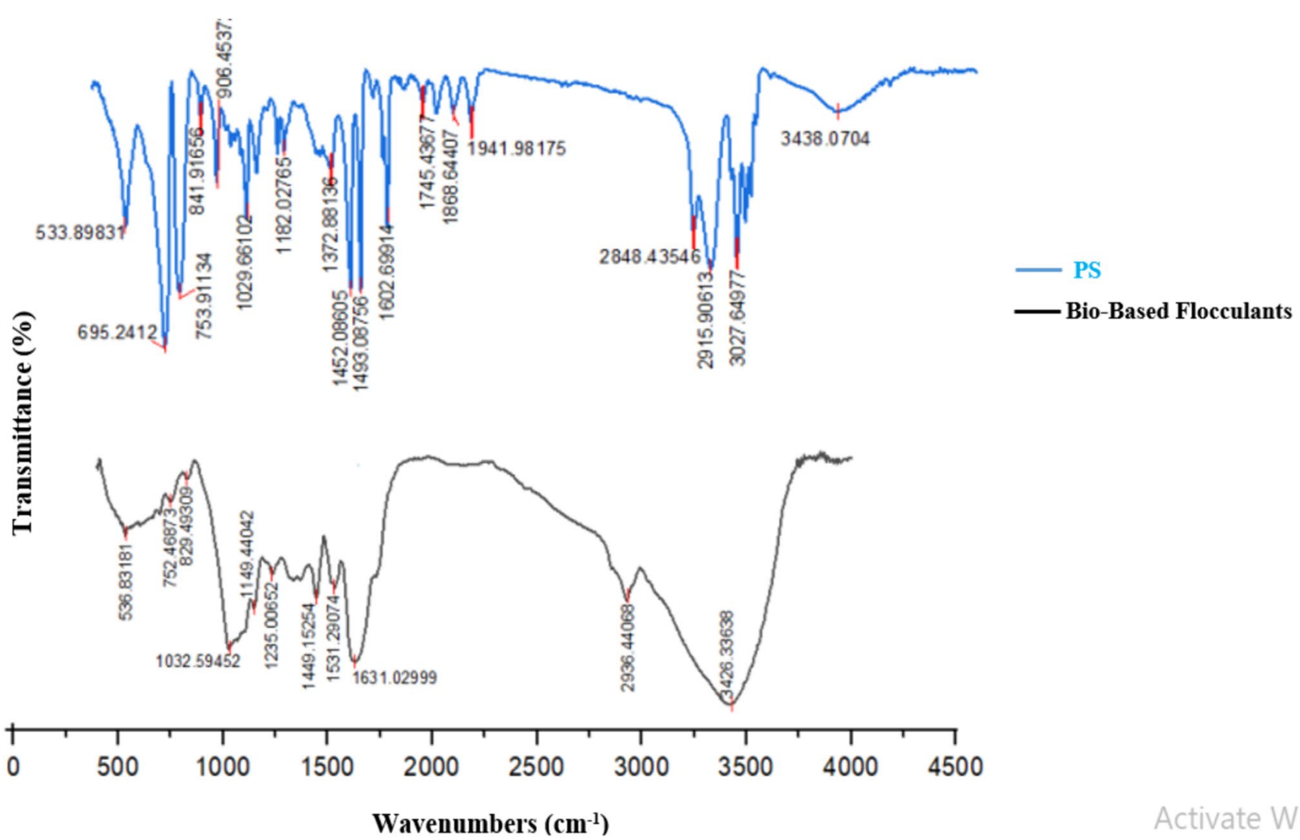

Fig. 5 FTIR spectrum of PS and Bio-based flocculants

benzene ring (Fang et al. 2010; Zhou et al. 2021). After the elimination process in Fig. 5, the peak corresponding to O–H groups in Fig. 5 was reduced to 3426.33 cm^{-1}. In the obtained spectrum, the asymmetric stretching of CH_2 has increased to 2936.44 cm^{-1}, indicating a significant change compared to the peak observed prior to the removal process. Additionally, the peak associated with the C=O group has decreased from 1493.08 to 1449.44 cm^{-1}. This reduction in intensity could be attributed to the formation of clots resulting from the adsorption of PS on *okra*. The peak at 1631.02 cm^{-1} is related to the amine groups in *okra*, which can reduce the repulsive force between the PS particles and contribute to the bridging between the particles, which is responsible for the coagulation-flocculation process (Ma et al. 2022). The benzene ring's substituted group, which is characteristic of PS, exhibited weak absorption peaks at 752.46 and 829.49 cm^{-1}. These peaks decreased following the coagulation process (Zhou et al. 2021). Also, the presence of polysaccharides in *okra* has been shown to help in bridging between particles, which is responsible for the coagulation-clotting process (Kim et al. 2020). Functional groups like the hydroxyl, the carbonyl, and the amine in the *okra* seed play a crucial role in the coagulation of the PS. Fard et al. (2021) highlighted that polysaccharides, proteins, carbonyl, carboxyl, and hydroxyl groups facilitate the bridging mechanism in coagulation processes (Fard et al. 2021). Similarly, another study emphasized the importance of amine, carboxyl, and hydroxyl groups in the charge neutralization mechanism during coagulation processes (Igwegbe et al. 2021).

Effect of effective factors on coagulation

Effects of pH on removal efficiency

After investigating the coagulation mechanism, the study also examined the impact of experimental conditions on the removal efficiency of MPs. The pH of the solution has a critical effect on the removal of MPs through coagulation and controls the surface charge of the particles (Han et al. 2020). Hence, it is crucial to elucidate the influence of pH on the removal efficiency. Figure 6 illustrates the removal efficiencies of PVC and PS MPs by the *okra* seed at various pH levels. In the PVC-*okra* seed system when the initial pH increased from 3 to 10, the removal efficiency of PVC was increased to 63.45% and the removal efficiency of PS is at an initial pH level of 3 about 59.8%, while those in the control groups without *okra* seed were 32.1 and 23.6%, respectively. These indicated that *okra* seed played an important role in the MPs removal. Throughout all stages of testing, the removal efficiency of PVC consistently outperformed that of PS. Studies have shown that PVC is more susceptible to electrochemical deposition and flotation, with lower

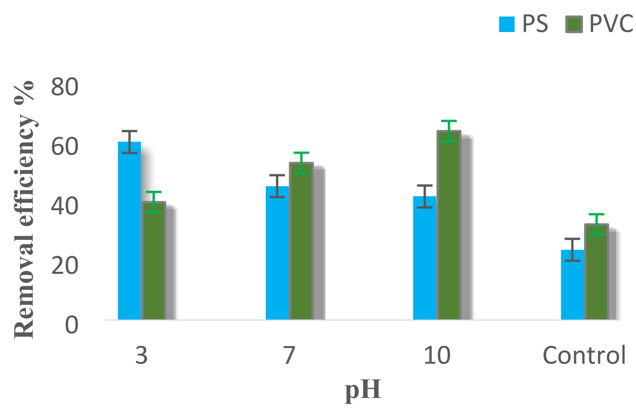

Fig. 6 Removal efficiency of PVC and PS MPs under various pH. $[PVC]_0 = 50$ mg/L, $[PS]_0 = 50$ mg/L; [*okra* seed]$_0 = 40$ mg/L

electrical resistivity, making settling easier (Wu et al. 2014). Statistical analysis demonstrated a significant correlation between the removal efficiency of MPs and pH for both PVC and PS (P-value < 0.003 and *P*-value < 0.02, respectively). Theoretically, at low pH levels, H + ions compete with organic ligands and active compounds from *okra*, thereby limiting their ability to establish bonds with the MPs (Kim et al. 2020). Conversely, at pH values above the isoelectric point, where surface charges are neutralized, the net charge of the MPs becomes negative, causing the polymer chains to expand. This expansion facilitates a bridging mechanism between the particles, promoting their removal. In general, the swelling of *okra* seed mucilage increases as the pH level rises. This phenomenon can be attributed to the enhanced ionization of the -COOH groups present in the mucilage at higher pH values. Consequently, there is a slight improvement in the removal efficiency of MPs in alkaline conditions compared to acidic conditions (Elkhalifa et al. 2021).

Moreover, it has been observed that the average size of flocs formed in alkaline conditions is larger compared to acidic conditions (Khan et al. 2023). This larger floc size is more favorable for effective sweep and sedimentation processes. Azizi et al. (2023) found that the rate of PS MPs removal by coagulants at pH 3 was substantially higher compared to other pH levels (Azizi et al. 2023).

Effects of microplastic concentration on removal efficiency

MP concentration is another factor that affects the removal efficiency. Figure 7 shows that as the concentration of PVC and PS increases from 20 to 100 mg/L, the removal efficiency decreases. The removal rate of PVC and PS in the control group without *okra* seed was 33% and 25.09%. Furthermore, a statistically significant difference was observed between the removal efficiency and MP dosage for both PVC and PS, respectively (*P*-value < 0.03, *P*-value < 0.04). In a

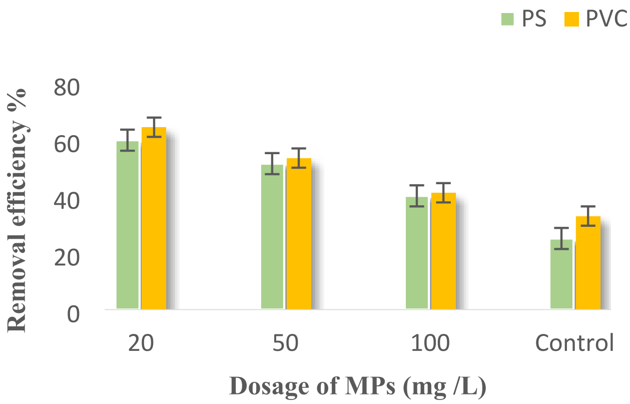

Fig. 7 Removal efficiency of PVC and PS MPs under various concentration MPs. $[\text{PVC pH}]_0=10$, $[\text{PS pH}]_0=3$; $[\textit{Okra}\ \text{seed}]_0=40$ mg/L

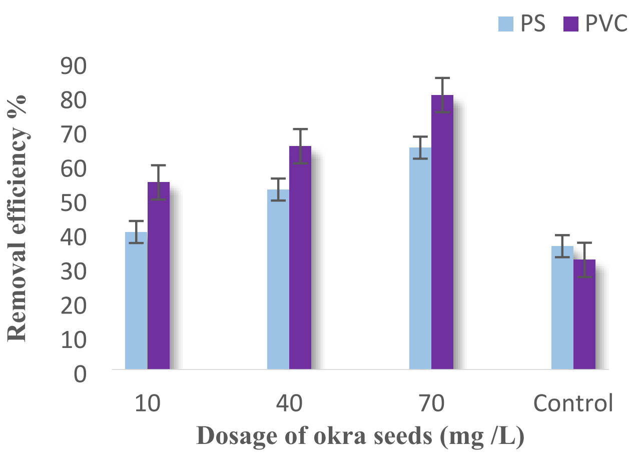

Fig. 8 Removal efficiency of PVC and PS MPs under coagulant various dosage. $[\text{PVC pH}]_0=10$, $[\text{PS pH}]_0=3$; $[\text{ PVC}]_0=20$ mg/L, $[\text{PS}]_0=20$ mg/L

study, it was confirmed that the removal efficiency of polyethylene MPs using *Chlorella vulgaris* algae decreased by increasing the concentration of PE from 250 to 400 mg/L (Nasrabadi et al. 2023a). The findings suggest that the removal efficiency of MPs is maximized within an optimal concentration range. However, beyond this range, the removal efficiency starts to decrease. At higher concentrations, the MPs can form a protective layer around themselves, reducing the contact between the MPs and *okra* seeds. Additionally, the repulsive forces between the particles at high concentrations contribute to their stability, making their removal more challenging (Nasrabadi et al. 2023a; Tang et al. 2022). Ziembowicz et al. (2023) discovered that during the coagulation of polyethylene and PVC in water using aluminum salt, an increase in MPs concentrations resulted in a slight decrease in removal efficiency (Ziembowicz et al. 2023).

Effects of coagulant concentration on removal efficiency

The effect of varying the *okra* seed coagulant dosage from 10 to 70 mg/L on the removal of PVC and PS MPs was evaluated. The results presented in Fig. 8 demonstrate a direct relationship between the dose of the coagulant and the removal efficiency.

By decreasing the coagulant dose to 10 mg/L, the removal efficiency of PVC and PS reached its lowest level of 54.62 and 40.14%, respectively. On the other hand, when the *okra* seed dose was increased to 70 mg/L, the removal efficiency significantly improved, reaching 64.76% for PS and 80.11% for PVC while those in the control groups without *okra* seeds are 36 and 32.6%, respectively. Statistical analysis revealed a statistically significant difference between the removal efficiency and coagulant dosage for PS (P-value < 0.01), but not for PVC (P-value < 0.726). These findings can be attributed to the mechanism of coagulation using the *okra* seed coagulant. At low coagulant doses, the formation of smaller and less dense flocs occurs, leading to poor sedimentation of the MPs. As shown in Fig. 4, the FTIR analysis of *okra* confirms the presence of carbonyl and hydroxyl groups, which are major components of carbohydrate molecules (Fard et al. 2021). These functional groups can be adsorbed on the surface of suspended colloids, allowing for the formation of bridges between the particles. In systems where the bridging mechanism is responsible for coagulation, increasing the dose of the coagulant generally improves the coagulation process (Kim et al. 2020). Therefore, the increase in *okra* seed coagulant dosage led to the formation of larger and more densely packed flocs (Jones and Bridgeman 2016), resulting in enhanced sedimentation and increased removal efficiency for both PVC and PS. Zhou et al. (2021) found that charge neutralization was dependent on coagulant and that removal efficiency increased with coagulant dosage because positive coagulant charges gradually decreased the ZP of MPs (Zhou et al. 2021).

Effects of electrical conductivity changes on removal efficiency

The study investigated the effects of various ions present in water samples on the removal efficiency of PVC and PS MPs. As shown in Fig. 9, the presence of NaCl being the most common compound in aquatic environments had little influence on the removal efficiency of MPs. This finding is consistent with a previous study (Ma et al. 2019a), in which the effect of inorganic salts on the coagulation process is influenced by the charge of the ions present in the solution (Jia et al. 2017). In contrast, the results indicate that SO_4^{2-} had a certain inhibitory effect on the removal efficiency of MPs (Duan and Gregory 2003). This is likely due to the fact that SO_4^{2-} is not useful for the binding of coagulant

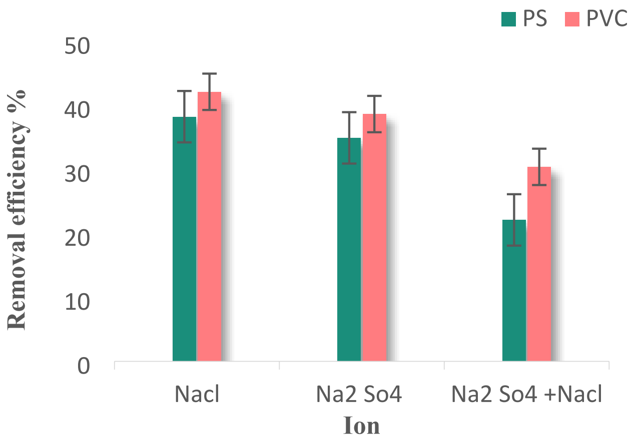

Fig. 9 Removal efficiency of PVC and PS MPs under ions various. $[PVC\ pH]_0 = 10$, $[PS\ pH]_0 = 3$; $[PVC]_0 = 20$ mg/L, $[PS]_0 = 20$ mg/L, [*okra* seed]$_0 = 40$ mg/L

hydrolyzates and MPs (Zhou et al. 2021). When the combination of Na_2SO_4 and NaCl was present, the removal efficiency of MPs was further lowered. As the salinity increases, Na^+ cations can easily attach to the negatively charged MPs through electrostatic interaction, preventing the adsorption of *okra* by the MPs (Perren et al. 2018). Statistically, a significant difference was found between the removal efficiency and EC for both PVC and PS MPs (P-value < 0.01 and P-value < 0.03, respectively). In summary, the findings of the study indicate that NaCl exhibits minimal impact on the removal efficiency of MPs. However, the presence of SO_4^{2-} and the combination of Na_2SO_4 and NaCl demonstrate inhibitory effects on the removal process of MPs.

Future prospective

We propose the integration of waste-to-energy technology, specifically pyrolysis, as a promising method for addressing the disposal of MPs. Pyrolysis offers a transformative approach by converting MPs waste into valuable products, such as oils and gases, while minimizing environmental impacts. By incorporating pyrolysis into the waste management process, we can effectively address the issue of MPs disposal, contributing to a more sustainable approach while simulta neously harnessing energy from the process. This indicates a promising direction for future research and development in the field of MPs waste management.

Conclusion

In summary, this research elucidates the removal performance and mechanism of PVC and PS MPs through the coagulation process utilizing *okra* seed. The study reveals that *okra* seed exhibits a notable removal performance on both types of MP and with PVC displaying a higher removal efficiency compared to PS. The coagulation process involves charge neutralization and bridging phenomena. According to the FESEM images, agglomeration adsorption was observed in the system. Furthermore, the FTIR spectra indicate the formation of new bonds during the interaction between the MPs and coagulants. The removal efficiencies of PVC and PS were the largest at pH levels of 10 and 3, respectively. The increase in MP concentration was conducive to the decreased removal performance. The increase in coagulant dos was conducive to the improved removal performance of MPs. NaCl and SO_4^{2-} had inhibitory and promoting effects on the removal efficiency of MPs, respectively.

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Data availability All necessary data are included in the document.

Declarations

Conflict of interest The authors declare that they have no conflict of interests.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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